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On the Cause of Large Daily River Flow Fluctuations in the Mekong River

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Abstract. Natural fluctuations in river flow are central to the ecosystem productivity of basins, yet significant alterations in daily flows pose threats to the integrity of the hydrological, ecological, and agricultural systems. In the dammed Mekong River, the attribution of these large daily flow changes to upstream regions remains mechanistically unexamined, a factor blamed on challenges in estimating the time required for large daily shifts in upstream river flow to impact the downstream regions. Here, we address this by integrating a newly developed sub-basin modeling framework that incorporates 3D hydrodynamic, response time, and hydrological models. This integration allows us to estimate the time required between two hydrological stations and to distinguish the contribution of sub-basins and upstream regions to large daily river flow alterations. Findings revealed a power correlation between river discharge and the required time to reach downstream stations. Significant fluctuations in the river's daily flow were evident before the advent of the era of human activities, i.e., before 1992. This phenomenon persisted throughout subsequent periods, including the growth period from 1992 to 2009 and the mega-dam period spanning from 2010 to 2020, with minimal variation in the frequency of events. Sub-basins were found to significantly contribute to mainstream discharge- a contribution which led to a significant contribution of sub-basins into mainstream daily large river flow shifts. The outcomes and model derived from the sub-basin approach hold significant potential for managing river fluctuations and have broader applicability beyond the specific basin studied.

1 Introduction

Natural flow regimes provide temporal and spatial fluctuations in river water level/flow, which are central to supporting productive environmental and ecological systems (Van Binh et al., 2020). However, large changes in river flow, mainly due to human intervention and climate change, pose a threat to ecosystem productivity and sustainable development in these

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences Discussions
Open Access EGU

basins, disrupting the integrity of the rivers, causing bank erosion (Darby et al., 2013), successive saturation and draining, and altering natural hydrological rhythms (Yoshida et al., 2020; Soukhaphon et al., 2021).

Water storage in dams, both in the mainstream and tributaries, and their operation can alter peak flows, increase base flows, and modify the frequency and variability range of discharge in rivers (Galelli et al., 2022). To date, more than 130 dams have been constructed in the basin, including 11 mainstream large hydropower dams in the upper Mekong (e.g., Lancang River), and many tributary dams in downstream sub-basins (see Figure 1). Plans are underway to construct additional dams in the basin to meet the ever-growing energy demand and for agricultural purposes (Kabir et al., 2022). Although the storage capacity of each tributary reservoir is typically small (e.g., < 5 km^3, see Figure S1 in the supplementary Material (SM)), the relatively considerable cumulative storage capacity of these reservoirs and their independent operation, as priorities vary among riparian countries, can intensify the hydrological alterations (Zhang et al., 2023). As a result, the lengths of dam-affected rivers increase due to significant disparities in water level/flow between the stretches above and below reservoirs (Graf, 2006), threatening the existing productive ecosystem that supports the food security of around 70 million people. This situation has fueled extensive research, including historical analysis of the flow regimes (Cochrane et al., 2014, Lu and Chua, 2021), assessments of Chinese dams' impacts on the downstream flow regime (Lu et al., 2014; Li et al., 2017; Räsänen et al., 2017), and studies on the impacts of constructed tributary dams in the lower Mekong (Piman et al., 2016). Observations by residents and other researchers suggest that human activities (e.g., dams) are responsible for altering the river's natural flow, impacting areas as far downstream as the Vietnamese Delta (Eyler and Weatherby, 2020).

In addition to human intervention, climate change, particularly changes in rainfall patterns, constitutes another significant driver of hydrological alterations in basins like the Mekong (Yun et al., 2020; Wang et al., 2021). Intense downpours lasting several hours or days have the potential to further exacerbate the downstream river flow alteration (Wang et al., 2017). In tributary-dominated rivers like the Mekong, undammed regions can deliver large discharges into the downstream areas, compounding the impact of these stressors and exposing the basin to daily water level fluctuations of 1-4 meters (MRC, 2011). These fluctuations trigger fish mortality by confining fish to small water bodies, altering spawning patterns and fish migration, and affecting agricultural and livestock production, market conditions, consumption patterns, and local demand (Burbano et al., 2020; Li et al., 2022), a concern recently raised by locals. Such daily fluctuations in water level/flow can influence critical phenomena like the flood pulse, which drives productivity in downstream regions such as the Tonle Sap Lake (Morovati et al., 2021a) in terms of agriculture and fishery (Chen et al., 2021; Wang et al., 2021). This requires a consistently higher water level in the Mekong River than in the lake to facilitate sustained inundation (Kummu et al., 2014). However, research on the daily assessment of large river flow alterations is limited, with most researchers focusing on monthly, seasonal, and annual scale studies. For example, before 2010, Lu and Siew, 2006 found that the flow regime in the basin remained roughly natural, a finding supported by later studies (Lauri et al., 2012; Morovati et al., 2023). Findings reveal that monthly discharge (water level) during the dry season from 2010 onward at Chiang Saen station located in Thailand (see Figure 2), the nearest one to the China border, has increased (decreased) by 98% (-1.55 m) compared to the years before 2010 (Lu and Chua, 2021).

Research conducted on flow regimes is rich, but modeling frameworks to quantitatively address the degree to which the downstream water level/flow changes are attributed to upstream regions are generally less developed. Such quantitative assessments pose challenges due to the lack of data for tributaries (Shin et al., 2020), which, at times, significantly contribute to the mainstream discharge (Zhang et al., 2023). Additionally, understanding the time required for shifts in upstream river flow to impact downstream cross-sections remains unknown. These uncertainties underscore the complexity of assessing and managing downstream river flow fluctuations in the context of climate change and human activities.

Here, we first identify the large daily river flow changes through the analysis of observed historical data over the last four decades. We then address the gaps mentioned above by developing an integrated modeling framework consisting of a highly accurate 3D hydrodynamic model to simulate daily water level/flow and velocity, a response time model to explicitly attribute the daily river flow changes at mainstream stations to their respective sub-basin and upstream station(s), and a hydrological model to provide daily discharge for tributaries lacking measured data. Our analysis based on the developed models expands on previous research on at least three aspects: (i) our approach enables us to quantitatively assess the regional contribution to downstream abnormal water level/flow shifts. Indeed, the analysis shifts the current conversations from how much water level/flow has historically altered, which contains small river flow changes existing even in undammed river basins, to how much upstream sub-basins have contributed to large daily water level/flow changes, which is significant for regional and transboundary development; (ii) the results offer essential insights into the time required for upstream river flow changes to propagate to downstream sub-basins. This facilitates improved management strategies for sub-basins, crucial for mitigating abnormal flow regime changes that pose threats to communities residing near the mainstream; (iii) these models and analyses provide insights into the concerns raised by locals regarding the role of climate change and human activities in the large daily river flow fluctuations in the Mekong River. Furthermore, the findings and the developed model can serve as a reference for understanding similar issues in other basins.

2 Material and Methods

2.1 Study area

With ~4500 km in length, the pan-shaped Mekong River constitutes the third most diverse aquatic ecosystem globally and ranks as the eighth largest in terms of annual runoff (Sabo et al., 2017). Its extensive length encompasses diverse geographical regions including deep valleys and lowland areas, which has facilitated both dam construction and agricultural development (Yoshida et al., 2020). The Mekong River is divided into two reaches, the upper course is known as the Lancang River within China where it originates from the Tibetan Plateau and is home to 11 large hydropower dams, and the lower reach is known as the Lower Mekong, where its surrounding sub-basins have been heavily impacted by agricultural activities and tributary dams (Zhang et al., 2023).

The hydrology of the basin is mainly influenced by an uneven distribution of rainfall, both spatially and temporally (Pokhrel et al., 2018). The wet season, occurring from June to November, sees substantial rainfall, resulting in approximately 345 km^3

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
Open Access
Discussions

of runoff. In contrast, the dry season, spanning from December to May, witnesses a significant decrease in basin-wide rainfall, leading to a notable drop, approximately 67%, in runoff delivered to the Delta region compared to the wet season. The mainstream runoff primarily stems from recharge by upstream sub-basins, tributaries, and precipitation.

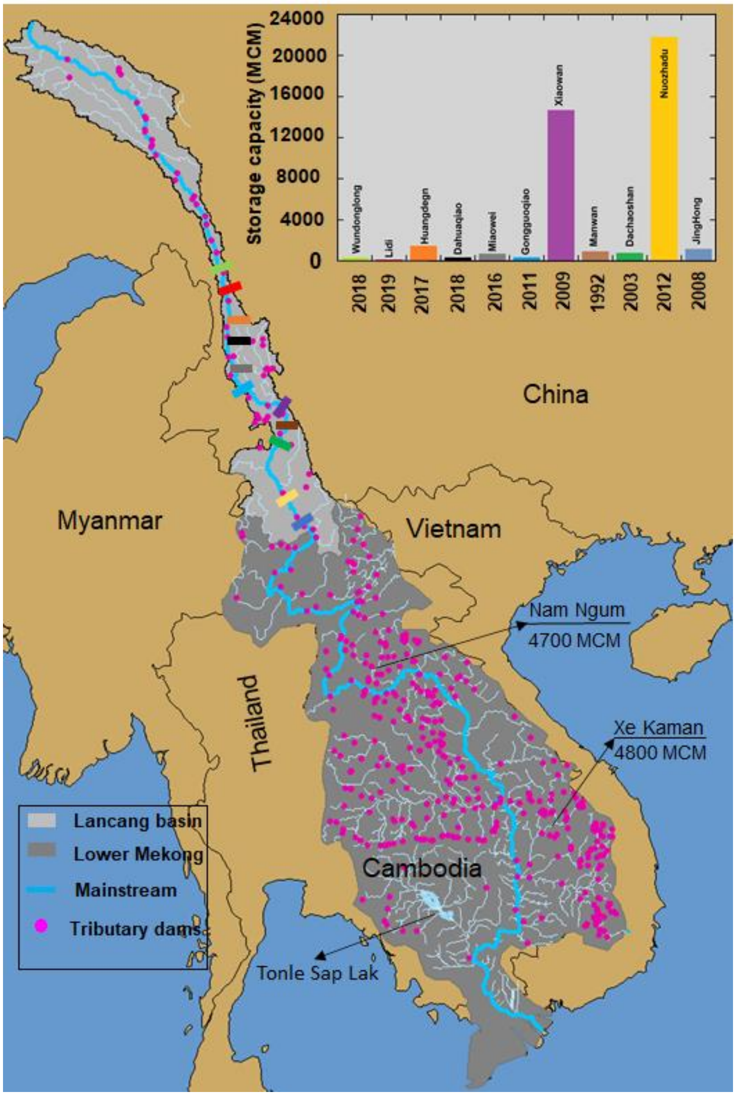

Figure 1: Map of the Lancang and lower Mekong basins, highlighting the extensive river network that dominates the region, along with the location of both constructed tributary and mainstream dams. The bar chart shows the total storage capacity of mainstream dams constructed within the Lancang River.

2.2 Methodology and Data Collection

105 The daily fluctuations in river flow are analyzed at seven mainstream gauging stations, a process pivotal in the formulation of our sub-basin modeling framework. Each sub-basin's delineated area precisely reflects the geographical extent exerting

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

influence on its respective downstream station. Our developed hydrological model, as detailed in sub-sections 2.2.2 and 3.1.1, demonstrates capability in generating time series discharge data for both mainstream stations and tributaries. Subsequently, these datasets serve as crucial input discharge data for defining the inlet boundary, complemented by outlet boundary specifications derived from water level data sourced from the Mekong River Commission (MRC), thus facilitating the integration of our hydrodynamic and response time models, as depicted in Figure 2.

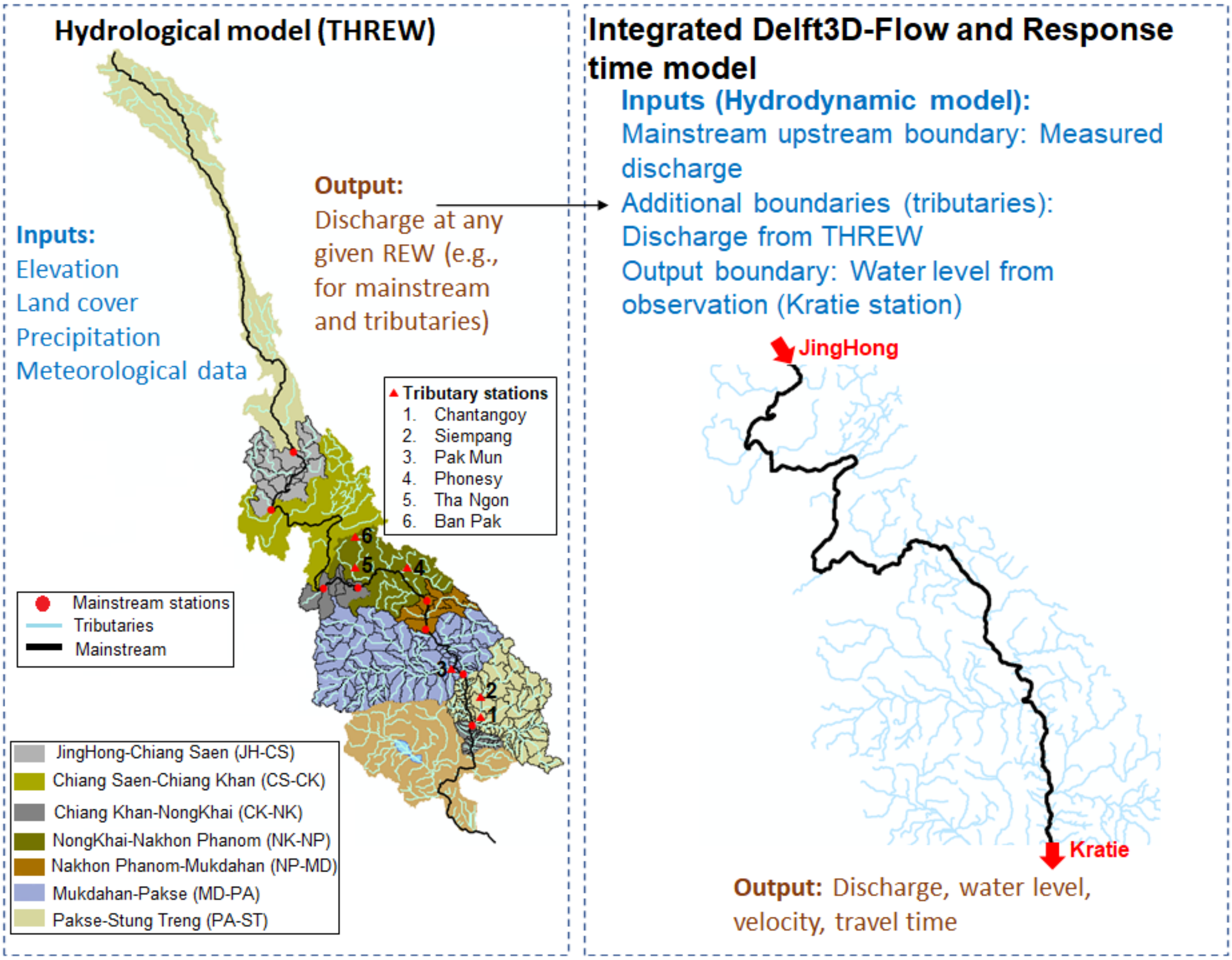

Figure 2: Illustration of developed integrated modeling framework. (a) The applied THREW hydrological model to the Mekong basin. (b) The defined computational domain in the developed hydrodynamic model for daily river flow fluctuations analysis. Note: In this study, the name of each defined sub-basin is based on its upstream and downstream stations

2.2.1 Data

For seven gauging stations extending from Chiang Saen (CS) to Kratie (KR) stations, continuous daily water level and discharge data were obtained from the MRC website from 1980 to 2020. Regarding tributaries, low-resolution discharge data

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
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EGU
Discussions

was accessible for six stations: Chantangoy, Siempang, Pak Mun, Phonesy, Tha Ngon, and Ban Pak Kanhoung. The locations of these stations are indicated in Figure 2. Additionally, low temporal resolution velocity data were measured at the Stung Treng (ST) station; however, velocity data was not available for stations located upstream of Stung Treng.

2.2.2 Hydrological Model

THREW—the Tsinghua Hydrological model based on the Representative Elemental Watershed (REW)—model serves as a physically and spatially distributed model that utilizes the REW method. This approach enables the basin to be partitioned into sub-basins based on selected hydrological stations for this study (see Figure 2). Its spatial feature allows each REW to be divided into various hydrological zones, capturing the basin's heterogeneous nature. The model incorporates various hydrological processes, such as glacier and permafrost dynamics, snowmelt, and rainfall, making it applicable to various regions within the Mekong basin. It demonstrates high performance in producing tributary flows in each REW (Cui et al., 2023).

Calibration of the model was achieved using an automatic parallel computation program, adjusting hydrological parameters (Nan et al., 2021a). The model has been extensively utilized in numerous studies, with more detailed information available in Tian et al. (2020).

Meteorological and precipitation data sourced from the MRC and CMA, i.e., China Meteorological Administration, served as primary inputs for the THREW model. Daily rainfall records were gathered from 166 hydrological stations for the Lower Mekong sub-regions and 12 stations for the Lancang sub-regions. Additionally, meteorological data including near-surface air pressure, air temperature, specific humidity, wind speed and direction, sunshine duration, and solar radiation were collected from 12 stations in both sub-regions. These datasets were utilized to calculate potential evapotranspiration using the Penman-Monteith Equation, which is a crucial parameter for the THREW model.

2.2.3 Hydrodynamic Model

Water level/flow modeling requires a hydrodynamic model to accurately capture the daily fluctuations in river flow. Flow velocity is equally essential in this study, as any daily change in upstream flow necessitates time for its downstream impact to manifest. The Delft-3D flow model was selected for implementing 3D simulations of the basin (Deltares, 2014). In this study, the simulation domain encompasses the river reach between JingHong and Kratie stations (~ 2200 km) (see Figure 2).

In the study area, the horizontal scale of the river significantly exceeds its depth, validating the shallow water assumption. The Navier-Stokes equations are solved for the river's incompressible flow. Given the curved computational boundaries typical of rivers like the Mekong, a spherical coordinate was utilized to prevent discretization errors resulting from undefined rectangular cells. The cyclic method was chosen for advection, and the $k-\varepsilon$ turbulence model, known for its superior performance, was implemented for simulations (Shi et al., 2022; Morovati et al., 2021b).

Land boundaries were defined wider than the river's main channel to accurately model large increases in discharge without being impacted by land boundaries. JingHong (JH) and Kratie (KR) stations were designated as the inlet and outlet

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
Open Access
Discussions

boundaries, respectively, with daily discharge and water level defined at these points. A vertical uniform profile was applied for the defined inlet discharge. Further details on model settings, including the computational meshing domain, can be found in the SM.

2.2.4 Response Time Model

This model is developed to determine the time required for upstream daily river flow to impact the downstream section, thereby allowing us to identify which upstream daily river flow shifts correspond to specific downstream daily fluctuations. The concept of response time reflects the degree of water exchange by depicting the residence time of water bodies while taking into account spatial heterogeneity. Therefore, to determine the response time of water and temporal dynamics within river systems, a sophisticated 3D response time (age) is developed, leveraging the hydrodynamic model within the Eulerian framework (Shi et al., 2023). Within this model, the trajectory of water entering the Mekong River is meticulously traced through the utilization of a virtual passive substance, commonly referred to as a tracer. Note that the defined tracer does not change the water density. The response time is how long it's been since it left a specific place, like the inlet boundary. We start counting the response time from zero when the water first leaves the inlet boundary. In this context, the term "age" signifies the average time of the tracer. This means response time is calculated by considering the ages of all individual tracers and weighting them based on their mass. To simplify, the introduction of water age concentration helps with averaging by combining the average response time of water tracers with their concentration. This creates a single variable that represents both the response time and abundance of the tracers. Both tracer concentration and age concentration follow advection-diffusion equations, which are based on the principles of mass conservation. This means that they account for the movement and spreading of tracers in the system while ensuring that mass is conserved throughout the process. The evolution of response time is governed by a set of equations (Equations 1-3), where a represents the response time, C is the tracer concentration, and α denotes the age concentration.

$$\frac{\partial C}{\partial t}+(\nabla.\vec{u})C+\frac{\partial wC}{\partial z}=\nabla.(D_h\nabla)C+\frac{\partial}{\partial z}(D_v\frac{\partial C}{\partial z}) \quad (1)$$

$$\frac{\partial \alpha}{\partial t}+(\nabla.\vec{u})\alpha+\frac{\partial w\alpha}{\partial z}=\nabla.(D_h\nabla)\alpha+\frac{\partial}{\partial z}(D_v\frac{\partial \alpha}{\partial z})+C \quad (2)$$

$$a=\frac{\alpha}{C} \quad (3)$$

In these equations, the components of horizontal and vertical velocity (diffusivity) are represented by $\vec{u}=(u,v)$ (D_h) and w (D_v), respectively. ∇ is the Hamiltonian operator ($\nabla=(\partial/\partial x, \partial/\partial y)$).

At the upstream (downstream) boundary of the Mekong River, designated as JingHong (JH) (Kratie (KR)), the boundary conditions for the tracer and age concentrations are defined as 1 and 0 (0 and 0), respectively. These defined boundary conditions facilitate the accurate simulation of response time along the primary flow path within the Mekong River.

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Furthermore, a cold start is implemented, initializing the entire domain with zero values for both tracer and age concentrations.

2.3 Scenario Setting

Our regional assessment of the basin is based on observed and simulated data spanning four decades, from 1980 to 2020. We divided this period into three distinct phases. The first phase, from 1980 to 1991, is designated as the pre-dam period due to the absence of large tributary and mainstream dams, as well as limited land cover changes aimed at improving farming practices. The second phase, spanning from 1992 to 2009, is categorized as the growth period, marked by the commencement of dam construction, including projects like the Manwan and JingHong dams, alongside observable changes in land cover (Zhang et al., 2023). The third phase, from 2010 onwards, is termed the mega-dam period, characterized by the construction of mainstream dams with a total capacity of 45 km^3. Additionally, a resurgence in tributary dam construction was observed in downstream sub-basins of the Lancang River, contributing to a total capacity of around 30 km^3.

In line with recommendations from the MRC regarding allowable hourly water level changes downstream of cascade dams (5 cm/hour or 1.2 m/day) (MRC, 2020), our study focuses on water level changes exceeding 1 meter, referred to as 'events.' The aim is to quantitatively assess the regional impacts contributing to these events.

3 Results

3.1 Model Validation

3.1.1 THREW Hydrological Model

The model calibration utilized data spanning from 2001 to 2009 across all selected stations, ensuring its accuracy and reliability. Subsequently, model validation was conducted for the years 1980 to 2000 to further assess its performance (Figure 3). Remarkably, the model exhibited good performance across all stations, consistently achieving an average Nash-Sutcliffe Efficiency (NSE) greater than 0.92. As depicted in Figure 3, the model effectively captured both high and low discharge events, resulting in discharge time series profiles closely aligning with observed data.

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
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Discussions

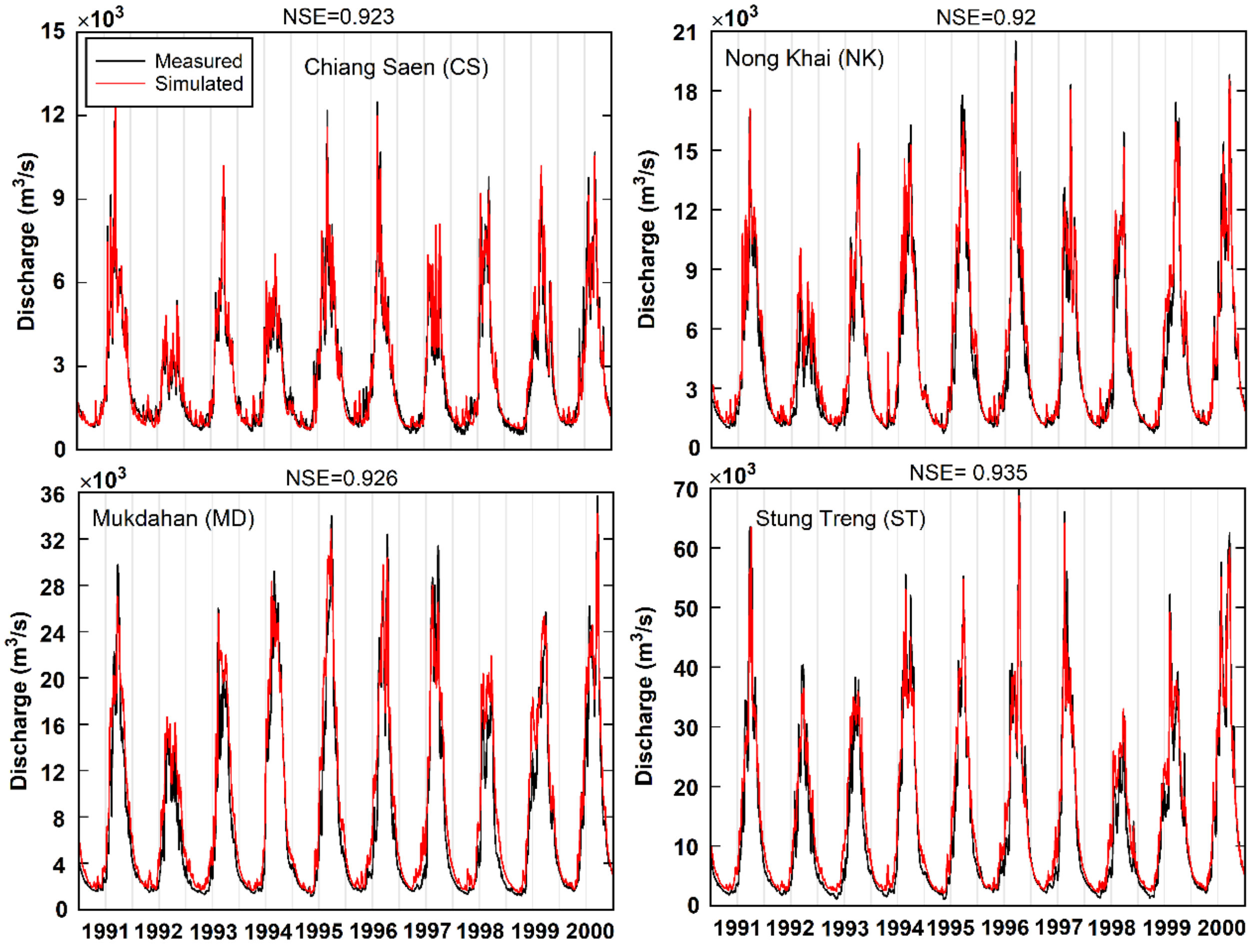

Figure 3: Comparison of the simulated time series discharge by THREW hydrological model with measured data over the validation period.

Comparable performance was attained for available tributary discharges, with the NSE values exceeding 0.88, indicating high accuracy. Additional details can be found in Section 5 of the SM.

3.1.2 Hydrodynamic Model

Accurately capturing the daily large fluctuations stands as a primary objective of this study, given its significant impact on regional contribution analysis. While a comprehensive comparison of the time series discharge and water level data yielded by the hydrodynamic model is conducted for all stations throughout the study period (see SM, section 3), Figures 4a and b illustrate water level and discharge profiles for a single month, showcasing notable river flow shifts at Chiang Khan (CK) and Pakse (PA) stations, respectively.

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
Discussions

In Figure 4a, observations over the span of a month reveal two substantial daily water level increases (1.5 m and 2.18 m) and a 1 m decrease in water level. Meanwhile, Figure 4b depicts Pakse station experiencing three consecutive large daily water level/flow increases. Notably, the developed model adeptly captures the river flow profiles at both stations, with a mean relative error (MRE) of less than 5%, underscoring its accuracy in modeling daily water level/flow shifts in the Mekong River.

Regarding flow velocity, data are solely available for the Stung Treng (ST) station with low temporal resolution. Daily flow velocity is compared with the model-derived velocity for the year 2018. A detailed point-by-point comparison indicates the model's relatively accurate simulation of flow velocity at this station, with an MRE of less than 7.1%. Comparable levels of accuracy are achieved for the years 2019 and 2020, as detailed in the SM, section 3.

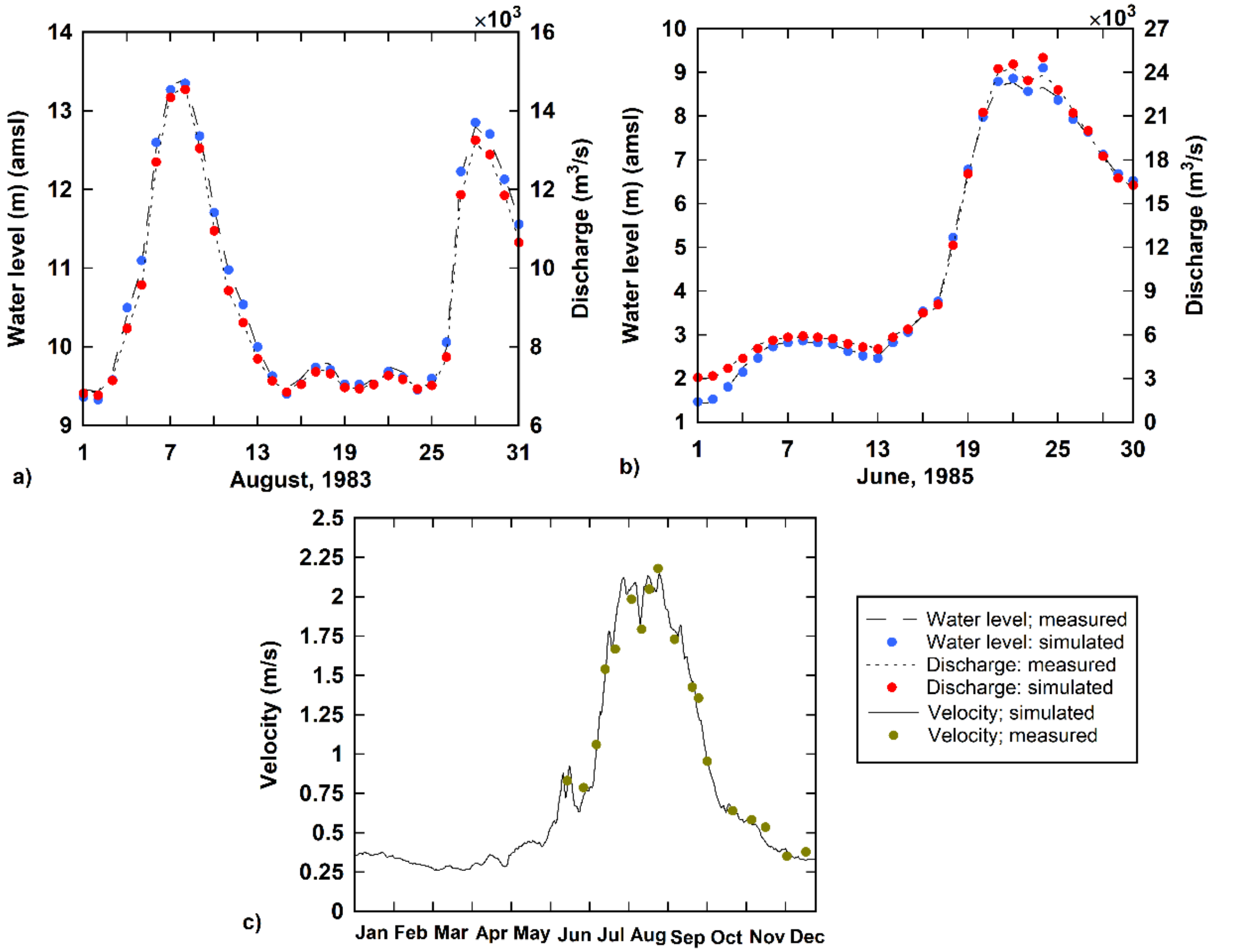

Figure 4: Comparison of water level and discharge profiles at two stations: a) Chiang Khan station and b) Pakse station. Part (c) depicts a point-by-point comparison of measured velocity with the hydrodynamic model for the year 2018.

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
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Discussions

3.2 Large daily water level/flow changes

Figure 5 illustrates significant fluctuations in water levels/discharges over a 24-hour cycle (daily) across all main hydrological stations during the pre-dam period (1980-1991). For comprehensive data covering the growth and mega-dam periods, please refer to the SM, section 4. Interestingly, such large river flow fluctuations occurred in the basin even before the construction of dams. During this period, a total of 143 events were recorded at these stations, with a notable concentration within the initial three months of the wet season, spanning from June to August. The number of daily fluctuations varies among the stations along the Mekong River. For instance, while the Pakse (PA) station encountered 28 events, its downstream station Stung Treng (ST) experienced only 7 events. This discrepancy underscores the significant influence of regional contributions on exacerbating or mitigating downstream discharge and subsequent water level changes (see Figure 7). Furthermore, the majority of these events were characterized by substantial increases in water level/discharge, aligning with observations typically associated with the wet season, spanning from June to November.

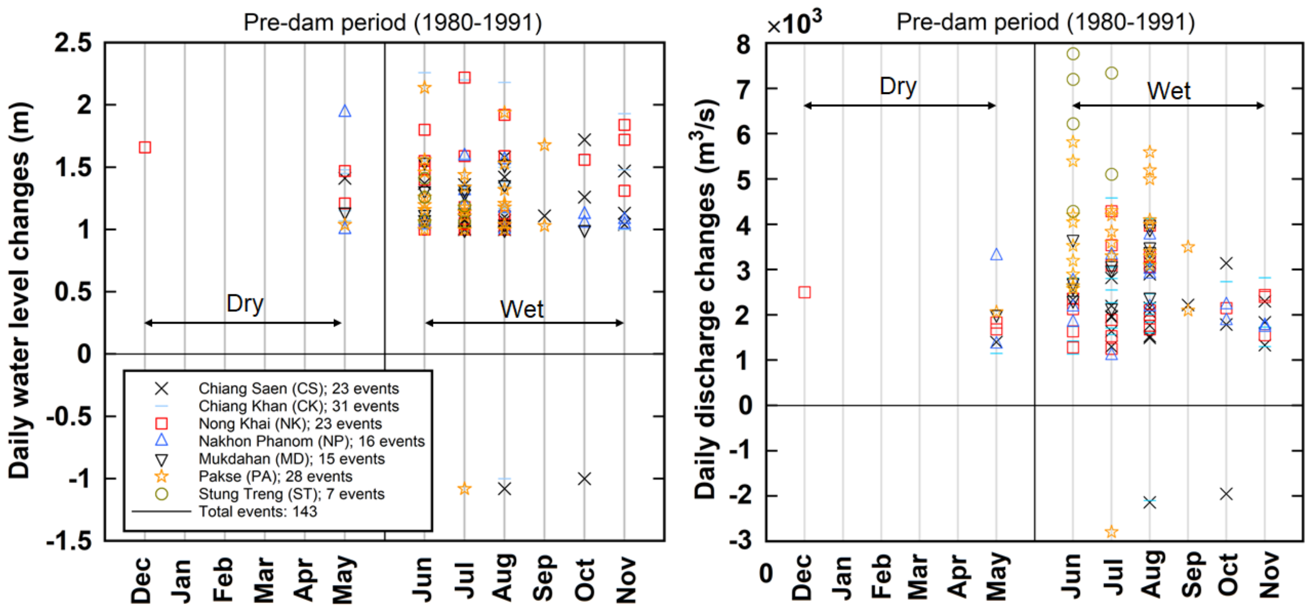

Figure 5: The daily river flow alterations greater than 1 m for the mainstream stations. Negative and positive values denote decreases and increases in water levels/discharges, respectively. Note: in this study, the wet season starts on June 1st and ends at the end of November.

3.3 Response Time

In this study, response time denotes the duration required for a daily flow change upstream to propagate and be recorded at a downstream gauging station. This allows us to determine the effects of upstream daily river flow changes on downstream shifts. Figure 6 illustrates the resultant graphs and their corresponding equations for each mainstream station, enabling the calculation of response time for daily river flow changes to their respective downstream stations. Generally, a higher

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

Hydrology and Earth System Sciences
Discussions

discharge at a given station corresponds to a shorter response time to its downstream station. This graph facilitates the determination of the minimum and maximum response time range for each daily river flow to reach its downstream station. For instance, at the Pakse station (PA), situated approximately 200 km upstream from the Stung Treng station (ST), the response times range from 1 to 10 days depending on the discharge at the Pakse station.

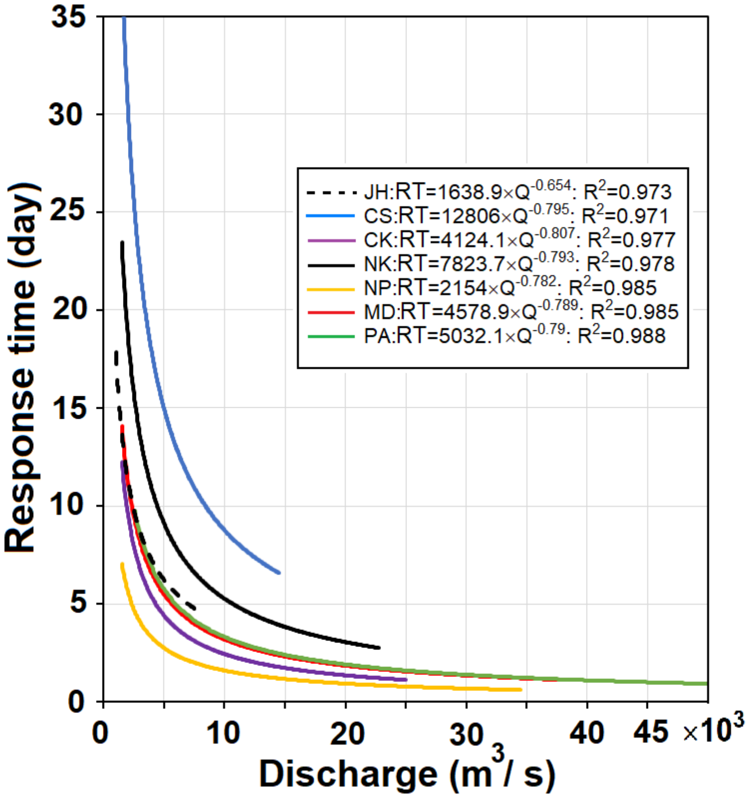

Figure 6: Response times (RT) equations and their corresponding graphs for all mainstream stations. Please note that the results presented in this figure are derived from the developed hydrodynamic model. These equations only calculate the response times based on the upstream station and do not consider the tributaries flowing into the mainstream

3.4 Contribution of sub-basin to mainstream flow

Figure 7 provides data on the cumulative average discharge at each hydrological station along the mainstream, reflecting contributions from both the respective sub-basin and its upstream station(s). Upon analysis, it becomes evident that most sub-basins in the Mekong River significantly contribute to the total downstream runoff, with the exception of the NP-MD and CK-NK sub-basins. In these cases, the contribution from each respective sub-basin to its downstream station is less than 5% of the total discharge passing through each station. On average, around 35%, 46%, and 45% of the total discharge during the wet season passing through Chiang Saen (CS), Chiang Khan (CK), and Nakhon Phanom (NP) stations originates from

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

respective sub-basins (Figure 7), indicating the significant role of these sub-basins in the daily river flow changes at their downstream stations.

Throughout the examined periods, there is no notable variance in the contribution of sub-basins and upstream stations to the downstream stations, except for the Nakhon Phanom (NP) station. At NP, a discernible increase of 10% in total runoff is observed in the recent decade compared to the pre-dam period (Figure S7 in the SM, amounting to ~2500 m^3/s).

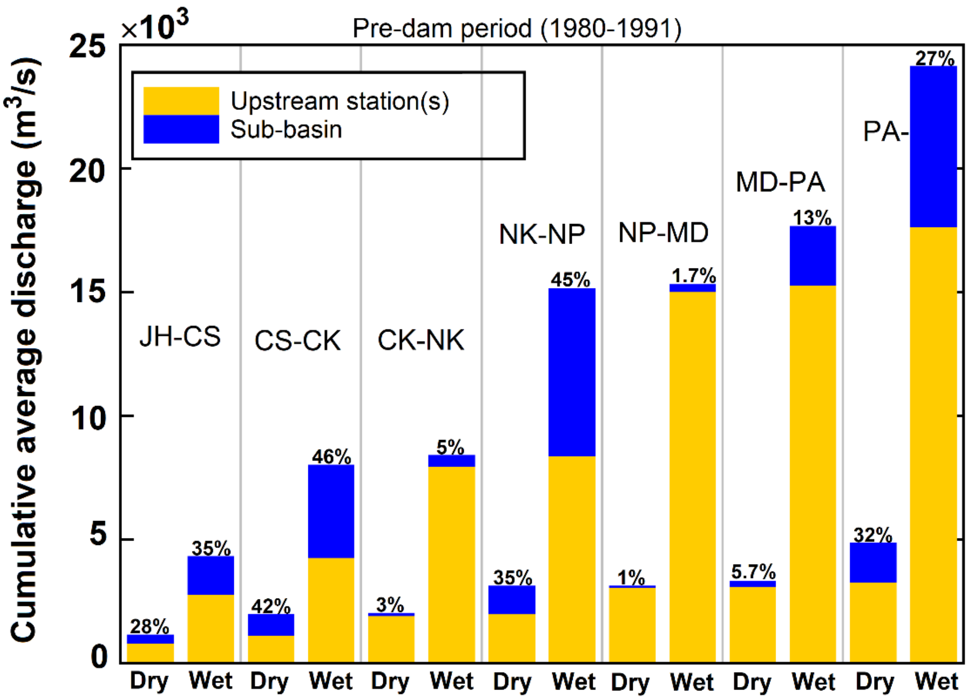

Figure 7: The cumulative average discharge data at each hydrological station along the mainstream of the river for wet and dry seasons, incorporating contributions from both the corresponding sub-basin and its upstream station(s). Note: For example, in this figure, 'JH-CS' refers to the area/sub-basin influencing the discharge at the Chiang Saen station from the JingHong station (JH).

3.5 Contribution of upstream sub-basins to large daily water level/flow increases

Figure 8 illustrates cumulative average daily discharge increases corresponding to the daily water level shifts exceeding 1m at each station along the Mekong River's mainstream, considering contributions from both the respective sub-basin and its upstream station(s). Chiang Saen (CS) station, situated closest to the Lancang River course, where Chinese mega-dams were recently constructed (2010-2020). Results reveal that during the pre-dam period, 67% of the Chiang Saen's discharge that resulted in water level shifts exceeding 1m can be attributed to its respective sub-basin. However, this contribution decreased to 63% during the growth period and further to 57% during to mega-dam period, indicating an impact that surpasses human activities in the Lancang basin.

This trend persists across other stations such as Chiang Khan (CK), Nakhon Phanom (NP), and Pakse (PA), where their respective sub-basins' contributions remained above 52% to daily discharge increases resulting in water level shifts

https://doi.org/10.5194/hess-2024-96
Preprint. Discussion started: 24 April 2024

exceeding 1m. The Mukdahan sub-basin exhibited the lowest contribution during the pre-dam period, at 10%. However, during the growth and mega-dam periods, the average contribution to daily discharge increases surged by 29% and 55%, respectively. Conversely, at the Nong Khai (NK) station, the contribution of its sub-basin to discharge increases saw a notable decline from 37% in the pre-dam period to 16% and 4% during the growth and mega-dam periods, respectively. Notably, the Nakhon Phanom (NP) sub-basin stands out for its substantial contribution, producing 64% (pre-dam), 79% (growth period), and 86% (mega-dam) of its downstream station's large daily discharge increases.

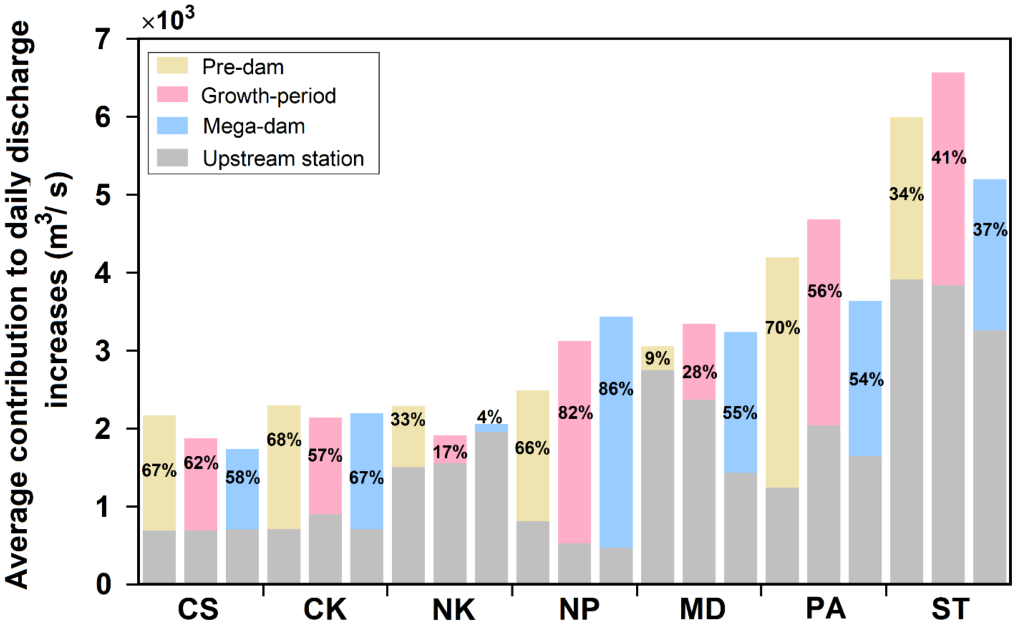

Figure 8: Average daily discharge increases corresponding to the daily water level shifts exceeding 1m at each station, considering contributions from both the respective sub-basin (colored parts) and its upstream station(s) (grey parts) for three defined periods. Percentage (%) shows the average contribution of each sub-basin in three examined periods.

4 Discussion

While minor alterations in the flow patterns of large rivers are expected, particularly in regions characterized by dominant tropical monsoonal climates and a high number of dam constructions, substantial shifts in river flow and water levels resulting from climate change and human activities can pose significant threats to the overall integrity of river networks and subsequent aquatic productivity. This study investigated the significant changes in river flow within the recently dammed Mekong basin. The analysis unveiled that, in the naturally wet conditions of the tropical lower Mekong basin, the basin experienced noteworthy large daily river flow and water level fluctuations (> 1m) even before the proliferation of anthropogenic activities such as large mainstream dams, tributary dams, and agricultural projects.

The basin's significant river flow changes primarily stemmed from increases rather than reductions in river flow, with the majority of these events occurring during the wet season over the past four decades. An approximate estimation of the rainfall received during the respective travel periods for each event reveals a consistency between the received rainfall and the contribution of the sub-basin to its downstream station during the pre-dam period, as illustrated in Figure 9. Conversely, the cumulative precipitation observed during the growth and mega-dam periods highlighted a discrepancy when some events are compared: despite larger precipitation received by the sub-basin during certain event response times, its contribution to downstream river flow change was less than that of events with lower precipitation. This phenomenon could be attributed to factors such as human activities and climate change, as indicated by marked events in Figure 9.

Upon daily analysis of large river flow changes along the Mekong River, this study found that regional assessment under a large-scale modeling framework can be observed as an effective approach rather than solely focusing on sub-basin study, as the impacts of upstream sub-basins are experienced by downstream sub-basin(s). This would also provide the possibility of exacerbating the impacts from upstream regions through coordinated management.

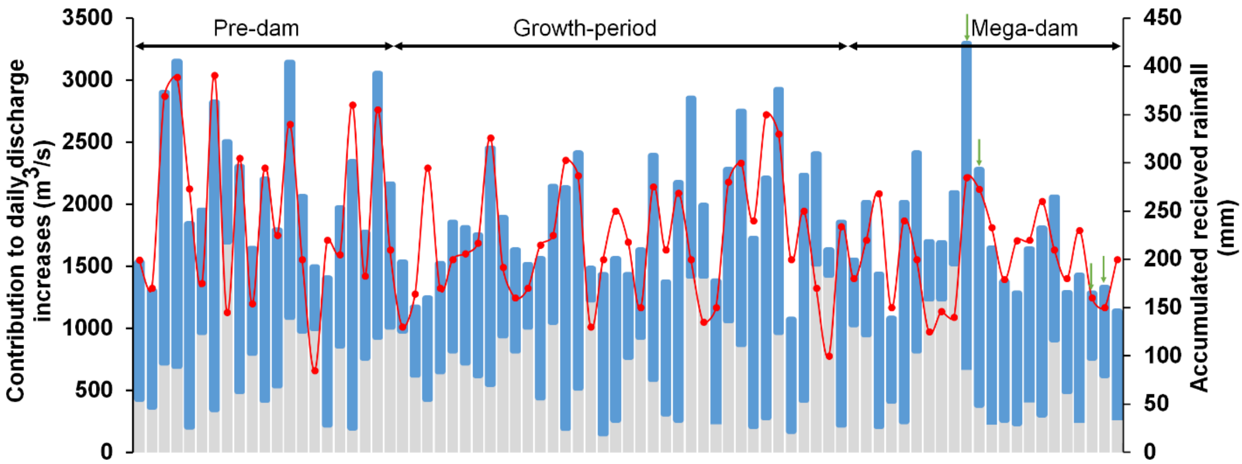

Figure 9: Daily large river flow discharge changes in Chiang Saen (CS) station for the three defined periods. The right y-axis shows the accumulated received precipitation in the JingHong-Chiang Saen sub-basin (JH-CS). Note: The total precipitation received does not precisely correlate with the discharge corresponding to the sub-basin contribution.

The basin experienced a notably heightened frequency of events resulting in a 1m increase in water level compared to reduction events, as illustrated by Figures 9 and 10. For example, at the CS station, there were 79 increased events while only 19 reduction events in the last four decades for all mainstream stations. This trend could possibly be due to a prevailing pattern of increased precipitation over multiple successive days, a phenomenon recurrent during the wet season (see section 9 in the SM for more details), and previously wet conditions of the region. Particularly noteworthy is the Lancang River's significant influence on daily discharge reduction at the Chiang Saen station (CS), accounting for 8 events. This influence is especially pronounced during the growth and mega-dam periods, with more than 66% of the CS station's large river flow change attributed to the Lancang region. This trend may be attributed to the compounded effects of climate change and human activities, such as the construction of large dams and agricultural projects after 1991.

An approximate estimation of precipitation drop – one of the indicators of climate change – before and after the response time for the JH-CS sub-basin indicates that the greater the reduction in precipitation, the higher the contribution of the sub-basin to downstream river flow decrease.

For stations like Nakhon Phanom (NP), where significant tributaries converge with the mainstream in their sub-basins, the contribution of the sub-basin to large discharge reduction outweighs that of the upstream station (59%). This can primarily be attributed to the presence of numerous tributary dams, agricultural activities (see Zhang et al., 2023), and the effects of climate change. These findings underscore the pivotal role of sub-basins in influencing downstream discharge and subsequent water level variations.

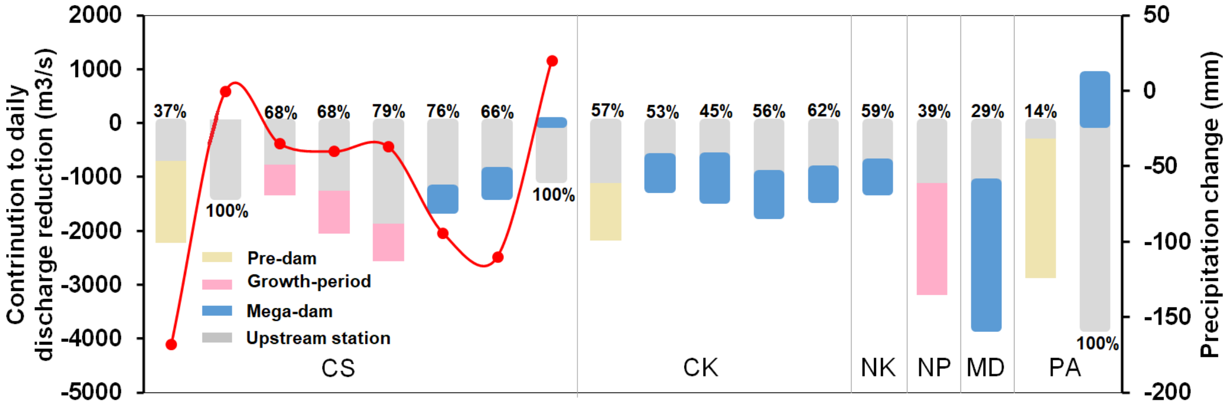

Figure 10: The daily discharge reduction at each mainstream station, leading to water level decreases exceeding 1m, based on upstream station(s) and their corresponding sub-basin. Percentages (%) indicate the contribution of the upstream station to the downstream hydrological station's large daily discharge change. The right y-axis indicates the rough estimation of precipitation reduction before and after the response time of each event

Any changes in the upstream regions require time to be experienced by downstream areas as river flow characteristics, including water level, discharge, and velocity are influenced. Based on the highly accurately developed hydrodynamic model, this study provided equations based on the discharge and velocity for the mainstream hydrological station (see Figure 11), this basin is lacking this data, which has great implications for future studies in terms of developing alarming systems for better management of the basin in the case of significant upstream changes in river flow as any upstream changes would impact the flow velocity and thus response time of the impacts. These findings also bring new insights into fishery studies based on the integrated modelling frameworks, which based on our research direction, further studies will be conducted in the near future.

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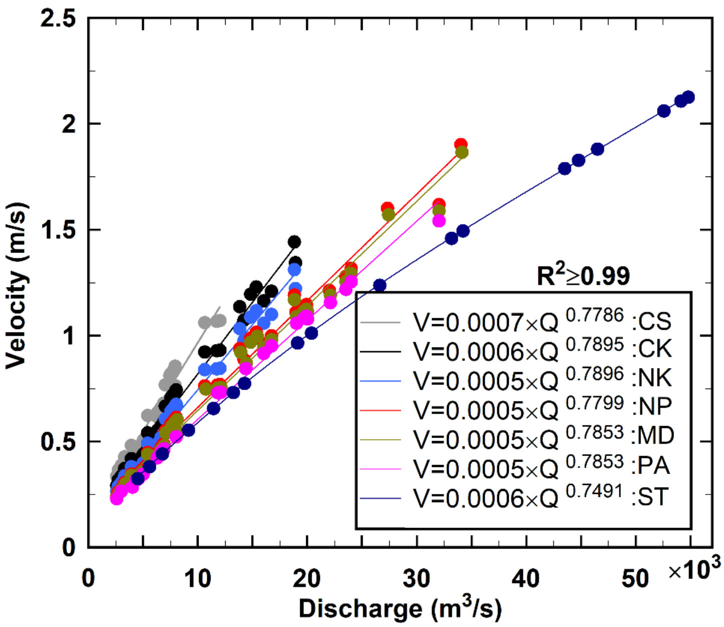

Figure 11: Velocity equations for all mainstream stations based on the yielded data by the developed hydrodynamic model. Note: *R^2* for all equations is >0.99

4.1 Limitations and Way Forward

i. This study was conducted based on the daily data as the basin lacks sub-daily data for discharge and water level. While this study provided new additional insights into the regional assessment of climate change and human activities under a large-scale basin study, sub-daily river flow data may be central to accurately capturing the river flow regimes of the dammed Mekong River. For example, at Ban Pakhoung (BP) station situated between CS and CK stations, the reported hourly water level data reveals that fluctuations exceeding 1 m were experienced by the mainstream even within a few hours, a relatively similar pattern observed for a few days (Figure 12). This pattern can trigger fish mortality by confining fish to small water bodies, thereby reducing biomass (Li et al., 2022). This might be a result of the hourly operations of tributary dams and received rainfall by the sub-basin, as any change in its upstream station, i.e., Chiang Saen (CS), requires more than a few days to be experienced by this station (see Figure 6).

In contrast, the water level profile did not experience fluctuations larger than 1 m when using daily data for the same period. Therefore, for the dammed basins, higher-resolution temporal data is recommended, as it may help in capturing sudden water release by dams. Downscaling of the data (e.g., water level and discharge) in the Mekong Basin may also bring new insights into how river flow changed during the pre-dam period on an hourly scale.

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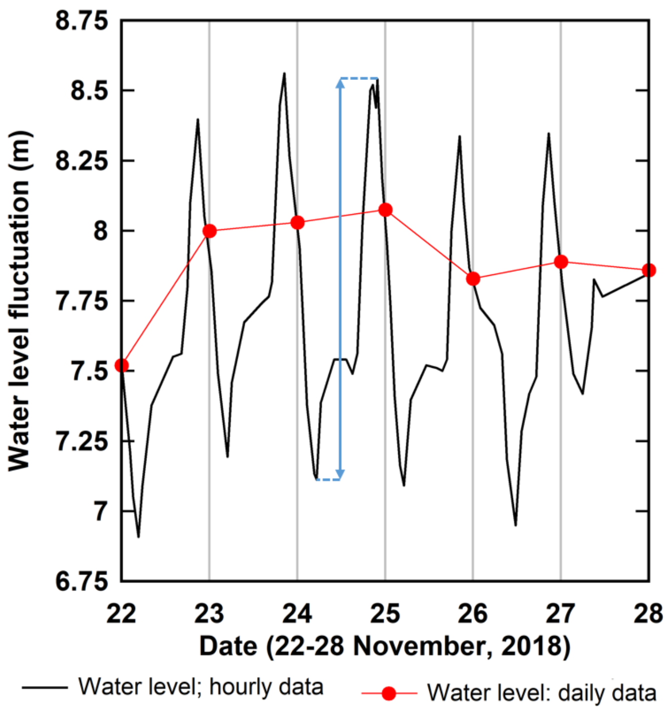

Figure 12: Sub-daily large water level fluctuations in the Ban Pakhoung (BP) station (see Figure 1, for the location of the station).

ii. This study was unable to explicitly address the drivers behind large flow fluctuations, a factor attributed to the lack of attributes of dams within the basin. Sufficient data on dam operation would pave the way for developing an integration of hydrological, hydrodynamic, and response time models with a dam model. Such integration would enable us to explicitly isolate the effects and gain a deeper understanding of the underlying mechanisms.

iii. The groundwater infiltration process was not incorporated into the developed hydrodynamic model. Although its impacts seem to be insignificant compared to the large discharge passing through mainstream, conducting groundwater measurements for each sub-basin, can further improve the accuracy of the model and thus reduce its uncertainty in attributing the upstream impact on downstream sub-basins.

iv. Although a large amount of sediment is transported from upstream reaches into downstream (160 Mt per year (Tian et al., 2023), the basin lacks reliable sediment data to be incorporated into the model. This data is central to updating the river bed configuration while the river is simulated by the model which can negatively influence the results.

v. Low temporal resolution data for velocity was available only for the Stung Treng (ST) station within the modelled area. The developed model accurately simulated flow velocity, water level, and discharge at this station, with the same accuracy in modelling water level and discharge for the upstream mainstream station. Upon this, this study developed equations based on the river discharge and flow velocity for all mainstream stations to produce a continuous time series of velocity data. Although the accuracy in modelling flow characteristics was relatively high in mainstream stations, the accuracy of the model in reaches between two consecutive stations remains unknown, as 1) the distance between two consecutive stations is large (for example from CS to CK is around 700 km), and 2) a more turbulent flow dominates the upstream reach of the Mekong River compared to its downstream reach. Providing more velocity data, even with low temporal resolution, would be important in producing detailed river flow regimes for the entire Mekong.

5. Conclusion

This study provided an analysis of large river flow changes across the Mekong River over the past four decades divided into three periods, pre-dam, growth, and mega-dam periods. In doing so, a sub-basin approach was developed incorporating physically-based hydrological, 3D hydrodynamic, and response time models. This approach enabled us to address the contribution of sub-basins to the daily significant river flow changes. Results of response time revealed a power correlation between the upstream daily river flow changes and its required time to reach downstream. Daily large river flow shifts exceeding 1 m were observed in various mainstream stations even before the construction of large hydropower dams in the basin, albeit different in the number of events, emphasizing the natural variability of the river system. These large daily river flow changes were also observed after human modifications in the basin; however, the frequency of such events did not significantly change.

Moreover, we have demonstrated the substantial contribution of Mekong sub-basins to mainstream discharge, with certain sub-basins contributing up to 46% to downstream mainstream stations. The JingHong-Chiang Saen sub-basin, for instance, contributed an average of 57% to significant river flow changes at the Chiang Saen station during the mega-dam period, surpassing that of the Lancang basin. This highlights the need for their consideration of basin-scale management strategies under a basin-wide approach.

Data availability

Water level, discharge, and velocity data are publicly accessible at https://portal.mrcmekong.org/home. The model code can be obtained upon reasonable request from the primary author of the paper.

Author contribution

KM and FT designed the study. KM, FT, LS, and MW developed the models, with KM implementing them. KM drafted the manuscript in close collaboration with FT and YP. PS and LS contributed to data curation. Throughout the study period, all authors engaged in discussions regarding the results, provided critical feedback, and approved the final version of the paper.

Competing interests

At least one of the co-authors is a member of the editorial board of the Hydrology and Earth System Sciences.

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